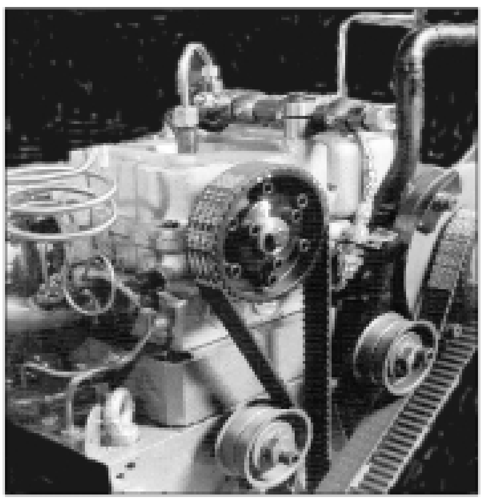
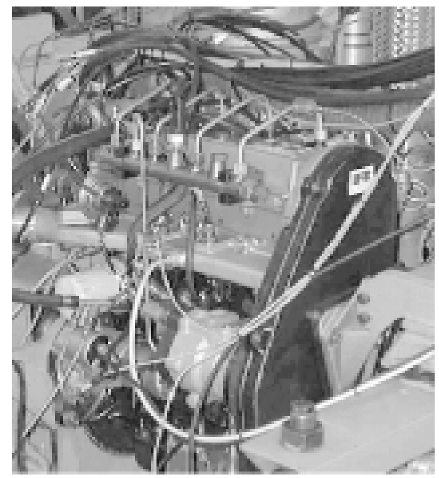
Emissions and Efficiency Targets: Advanced Technology Reciprocating Internal Combustion Engines





California Advanced Reciprocating Internal Combustion Engines Collaborative (ARICE) Workshop

Sacramento, 10 July 2001

Presented by: James C. Paul, P.E., Senior Engineer, Ricardo, Inc.

Presentation Outline

- Introduction
- Review of Drivers: Lower Emissions, Improved Performance
- Engine and Aftertreatment Technologies
- Conclusions

Goal of Presentation

❑ Goal of ARICE:

To facilitate research and development of advanced reciprocating internal combustion engine systems that are

- **Super Efficient**
- **Ultra-Clean**

For: power generation and stationary applications throughout California.

❑ Goal for this Presentation:

- **To define emissions and efficiency targets for these engines.**
- **To list engine technologies under development aimed at improving efficiency and lowering emissions.**

Roadmapping Process

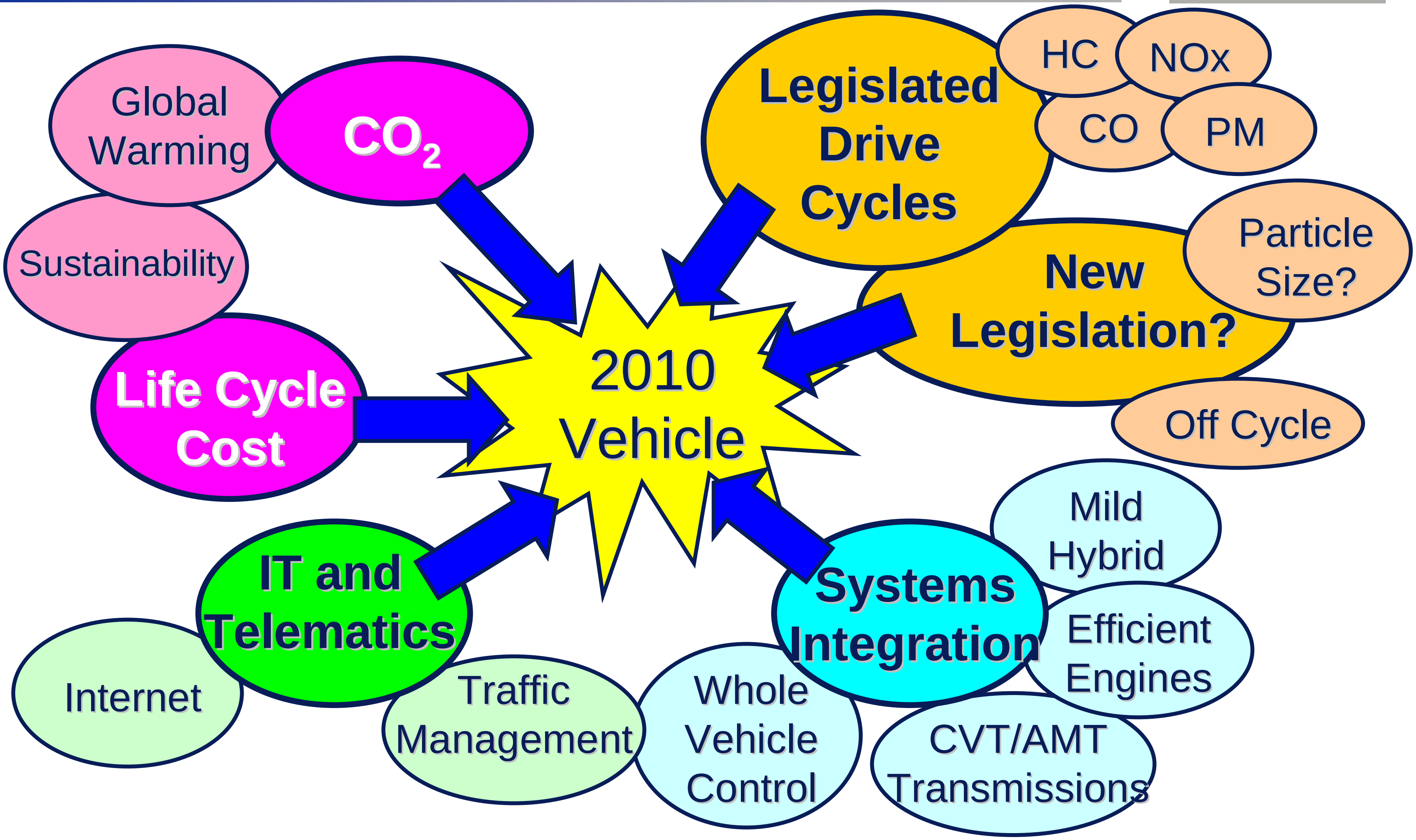
Ricardo has conducted an internally funded research project to define future engine technologies:

- This is the most comprehensive evaluation of future technologies ever carried out by Ricardo
- It is the collective view of technical specialists from Ricardo worldwide
- Process has involved:
  - **80** technical specialists from across the Ricardo Group in brainstormings and group/individual discussions
  - Confidential dialogue with 11 client groups
  - Input from a number of specialist technical publications (Standard & Poors, Delphi X, FT etc)
  - Legislative groups

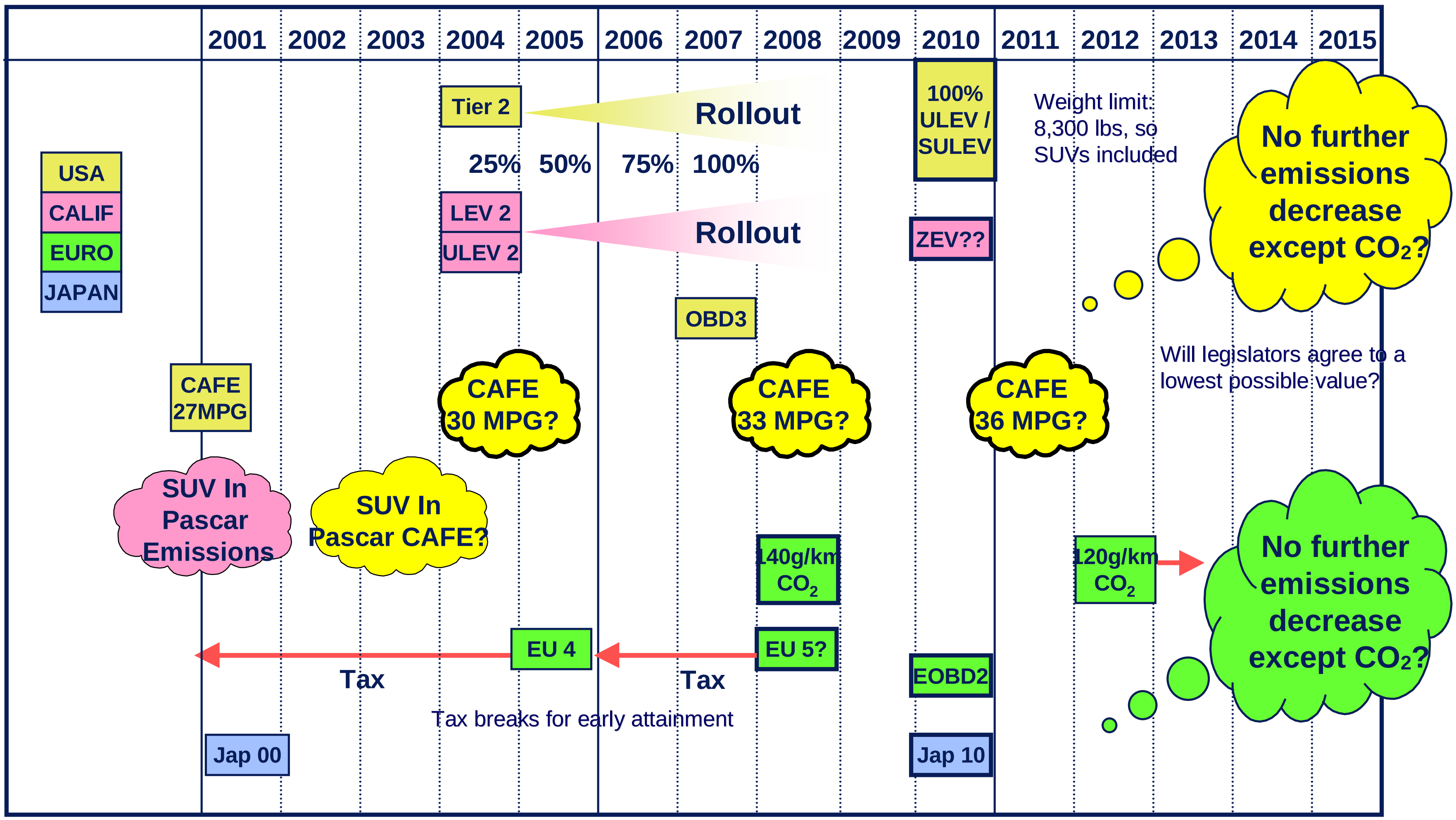
Technology Roadmap Megatrends

- **Environment - CO_2 (fuel efficiency) and Life Cycle Cost**
  – Global warming (Europe and Japan), increasing desire for sustainable power
  – Fuel cost (Europe), overseas oil dependence (USA)
- **Brand differentiation**
  – Increasing market demand for differentiation and niches
  – Must deliver diversity of products quickly to market
- **Systems Integration**
  – To maximize the effectiveness of next generation technology
- **Information Technology**
  – Performance History, Internet Connections and Control

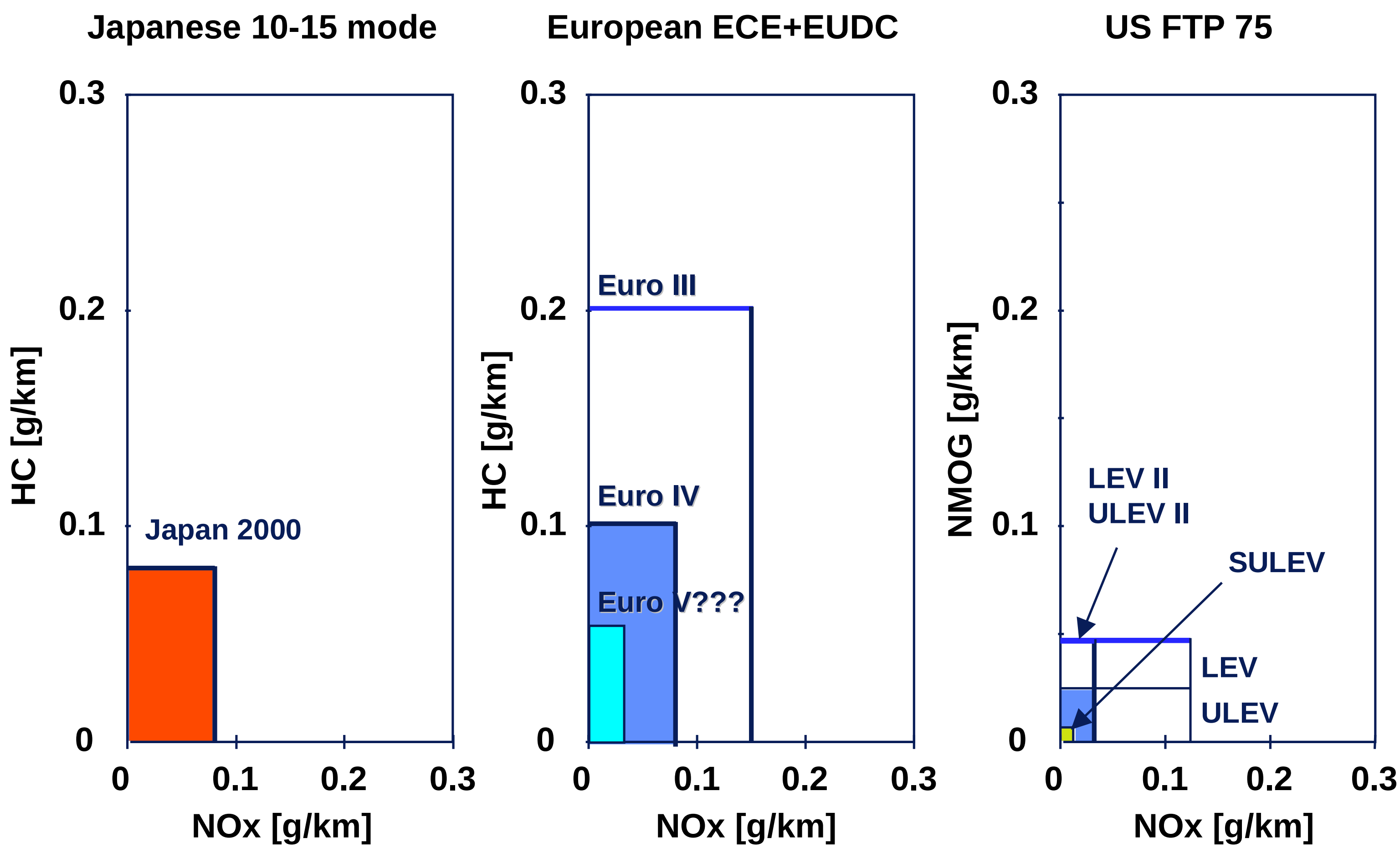
Global Drivers



Market Drivers
Global Emissions Legislation



Comparison of Worldwide Gasoline Vehicle Emissions Legislation



Much of the new technology is being driven by passenger vehicle emissions limits.

Title 13, California Code of Regulations, Section 2423

Exhaust Emissions Standards: Off-Road Compression-Ignition Engines

Exhaust Emissions Standards

Maximum Rated Power	Tier	Model Year	NO_x	HC	$NMHC+NO_x$	CO	PM
kW<8	Tier 1	2000-2004	—	—	10.5	8.0	1.0
	Tier 2	2005 and later	—	—	7.5	8.0	0.80
8<kW<19	Tier 1	2000-2004	—	—	9.5	6.6	0.80
	Tier 2	2005 and later	—	—	7.5	6.6	0.80
19<kW<37	Tier 1	2000-2003	—	—	9.5	5.5	0.80
	Tier 2	2004 and later	—	—	7.5	5.5	0.60
37<kW<75	Tier 1	2000-2003	9.2	—	—	—	—
	Tier 2	2004-2007	—	—	7.5	5.0	0.40
	Tier 3	2008 and later	—	—	4.7	5.0	—
75<kW<130	Tier 1	2000-2002	9.2	—	—	—	—
	Tier 2	2003-2006	—	—	6.6	5.0	0.30
	Tier 3	2007 and later	—	—	4.0	5.0	—
130<kW<225	Tier 1	1996-2002	9.2	1.3	—	11.4	0.54
	Tier 2	2003-2005	—	—	6.6	3.5	0.20
	Tier 3	2006 and later	—	—	4.0	3.5	—
225<kW<450	Tier 1	1996-2000	9.2	1.3	—	11.4	0.54
	Tier 2	2001-2005	—	—	6.4	3.5	0.20
	Tier 3	2006 and later	—	—	4.0	3.5	—
450<kW<560	Tier 1	1996-2001	9.2	1.3	—	11.4	0.54
	Tier 2	2002-2005	—	—	6.4	3.5	0.20
	Tier 3	2006 and later	—	—	4.0	3.5	—
kW>560	Tier 1	2000-2005	9.2	1.3	—	11.4	0.54
	Tier 2	2006 and later	—	—	6.4	3.5	0.20

Exhaust Emissions Standards

Voluntary standards. Engines may be designated “Blue Sky Series” engines through the 2004 model year by meeting the voluntary standards contained in the table below which apply to all certification and in-use testing. Blue Sky Series engines shall not be included in the Averaging, Banking, and Trading program.

Voluntary Emission Standards
(grams per kilowatt-hour)

Maximum Rated Power (kW)	$NMHC+NO_x$	PM
KW<8	4.6	0.48
8<kW<19	4.5	0.48
19<kW<37	4.5	0.36
37<kW<75	4.7	0.24
75<kW<130	4.0	0.18
130<kW<560	4.0	0.12
KW>560	3.8	0.12

Exhaust Emissions Limits: U.S. EPA Non-Road Engines, Tier 2 & 3

	Power Range	Date	NOx + NMHC [g/kW.h]	CO [g/kW.h]	Particulate [g/kW.h]
Tier 2	<8 kW	2005	7.5	8.0	0.80
	8-19 kW			6.6	
	19-37 kW	2004		5.5	0.60
	37-75 kW			5.0	0.40
	75-130 kW	2003	6.6		0.30
	130-225 kW			3.5	0.20
	>225 kW	2001	6.4		
Tier 3	37-75 kW	2008	4.7	5.0	*(0.20)**
	75-130 kW	2007	4.0		*(0.15)**
	130-225 kW	2006		3.5	*(0.10)**
	>225 kW	2006			*(0.10)**
	**Note: Tier 3 particulate limits to be decided. Figures given are estimates*				

U.S. EPA Emissions Standards

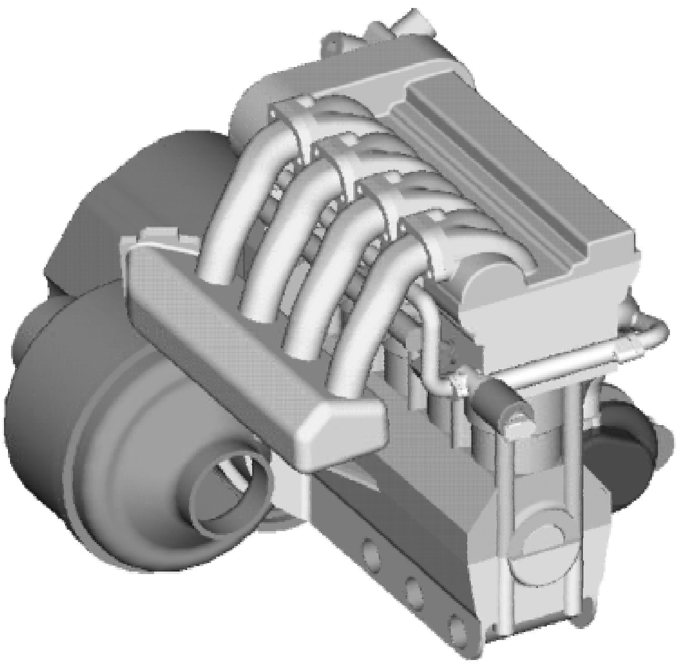
- Heavy-Duty Diesel Engine Regulations
  - 0.2 g/bhp-hr NO_x
  - 0.01 g/bhp-hr PM

  This represents a 90% reduction from 2004 regulations
- Phased in during 2007 – 2010
- EPA Rule issued January 18, 2001 requiring 80% of all on-road diesel fuel to have less than 15 ppm sulfur starting in 2006.

Source: U.S. Department of Energy, "Role of Low Sulfur Diesel Fuel in Future Clean Transport Policy", Dr. James J. Eberhart, 3rd Biennial World Truck Conference, Monterey, CA, March 4-6, 2001.

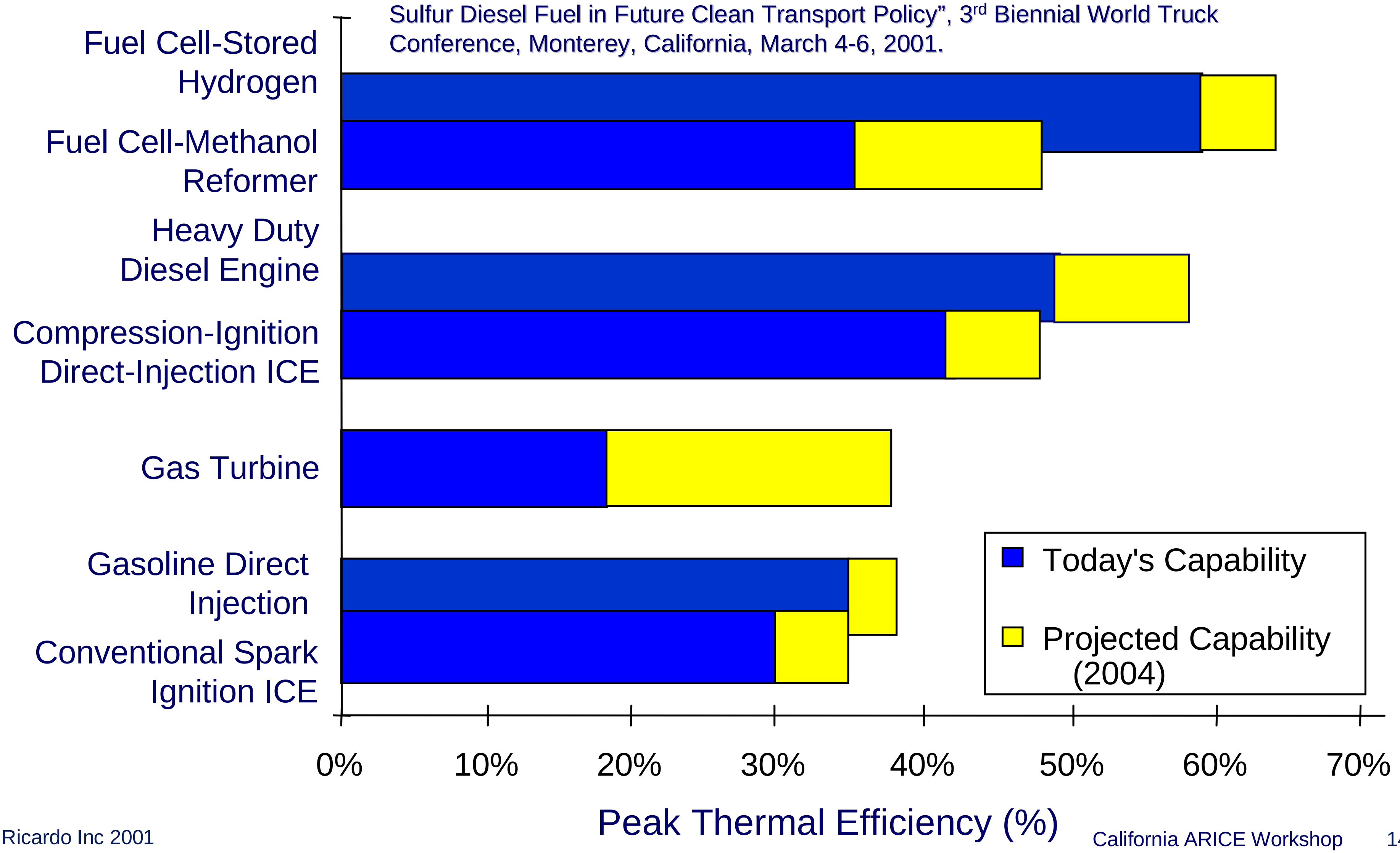
Gasoline Engine Developments

- New concepts being researched at major vehicle manufacturers (Model Year 2003)
  - Direct Injection (DI) Gasoline
  - Homogeneous Charge, Stoichiometric, Stratified Charge
  - Lean Boosted DI Gasoline
- Potential CO_2 emissions & fuel economy of future Diesel engine with
  - Gasoline engine driving characteristics
  - Better refinement
  - Lower weight and unit cost
- Shares many technologies with Diesel concept:
  - Light, compact structure
  - FMED and AMT
  - Electric Ancillaries

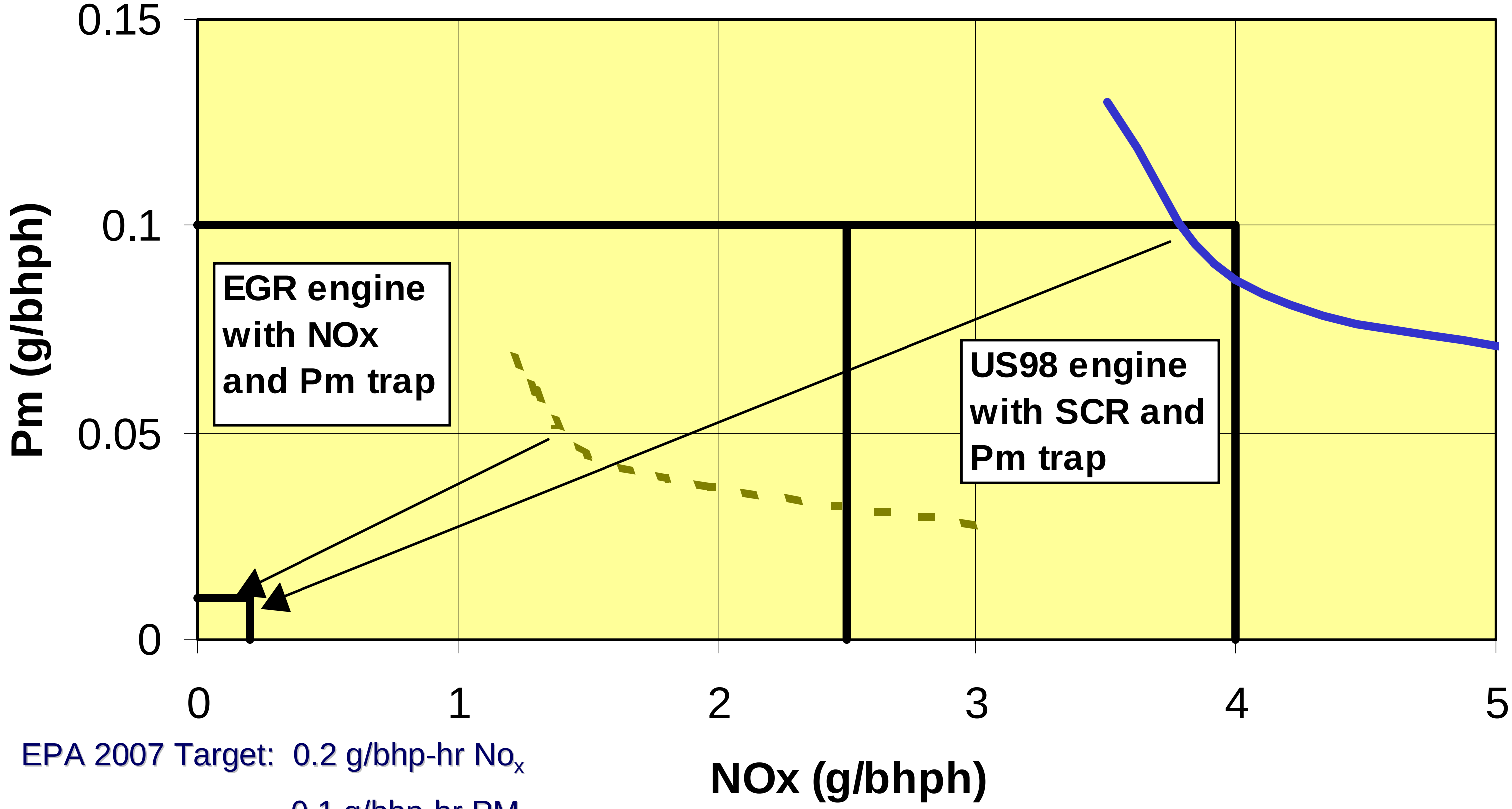


Comparison of Energy Conversion Efficiencies

Source: U.S. Department of Energy, Dr. James J. Eberhardt Presentation: "Role of Low Sulfur Diesel Fuel in Future Clean Transport Policy", 3rd Biennial World Truck Conference, Monterey, California, March 4-6, 2001.



Potential HD Technologies for US07



EPA 2007 Target: 0.2 g/bhp-hr No_x

0.1 g/bhp-hr PM

Emissions Control Technology for Heavy Duty

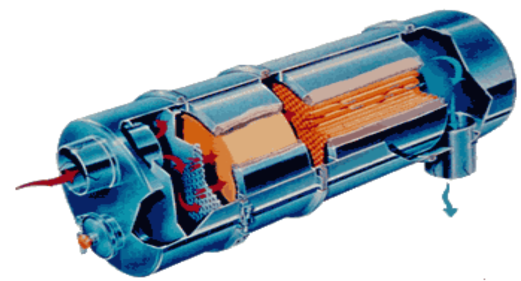
The proposed emissions levels for US07 and Euro IV, are likely to require aftertreatment

Given the particulate levels as well as political pressure, it can be assumed that the use of particulate filters will have a very high probability

A form of NOx aftertreatment will probably be necessary. The utilization of either EGR (exhaust gas recirculation), SCR (selective catalytic reduction), or LNT (lean NO_x trap) systems will depend on the application and the market

Emissions Control Technology for Heavy Duty Engines

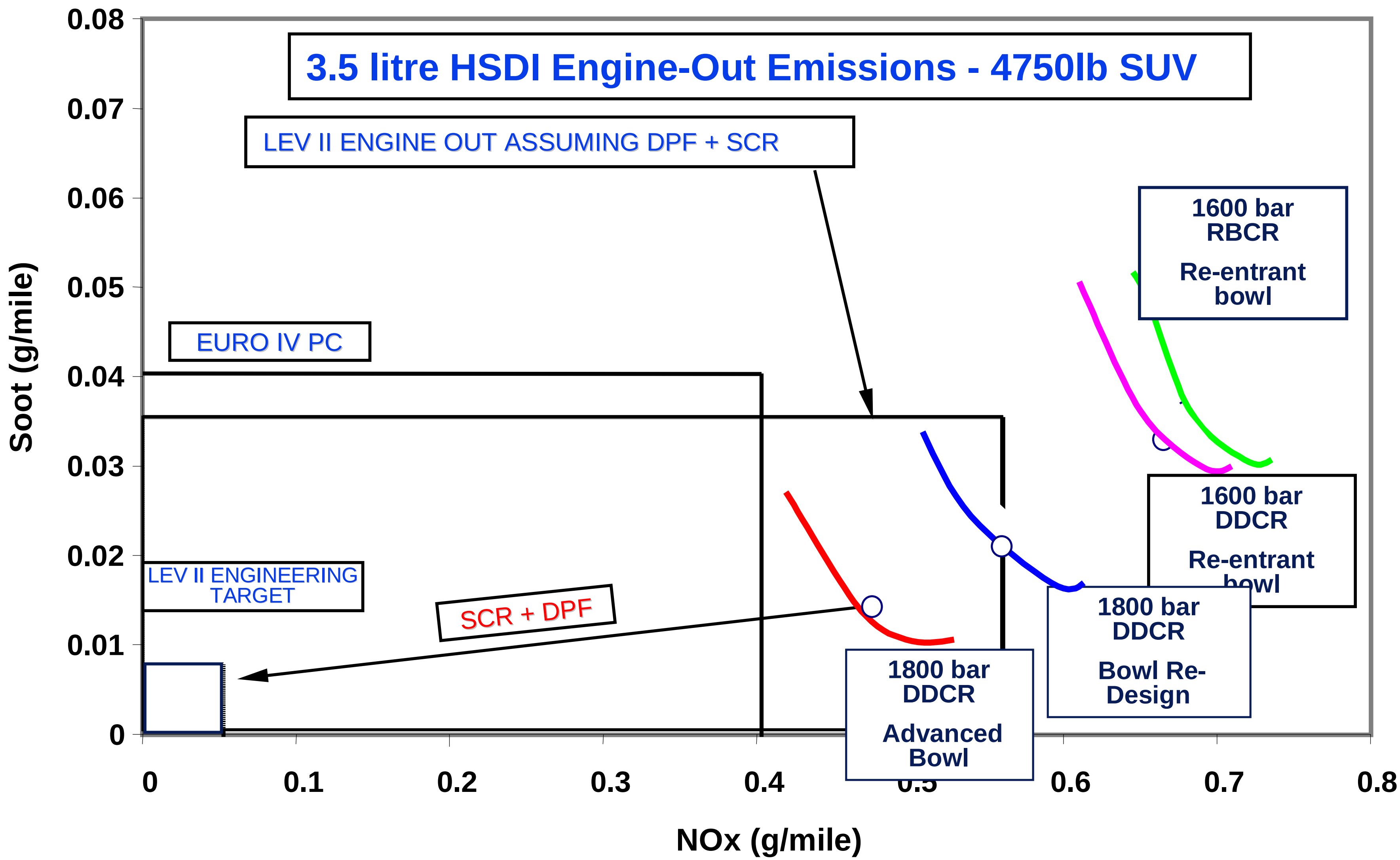
Current Development Programs: Heavy-Duty Diesel Manufacturers



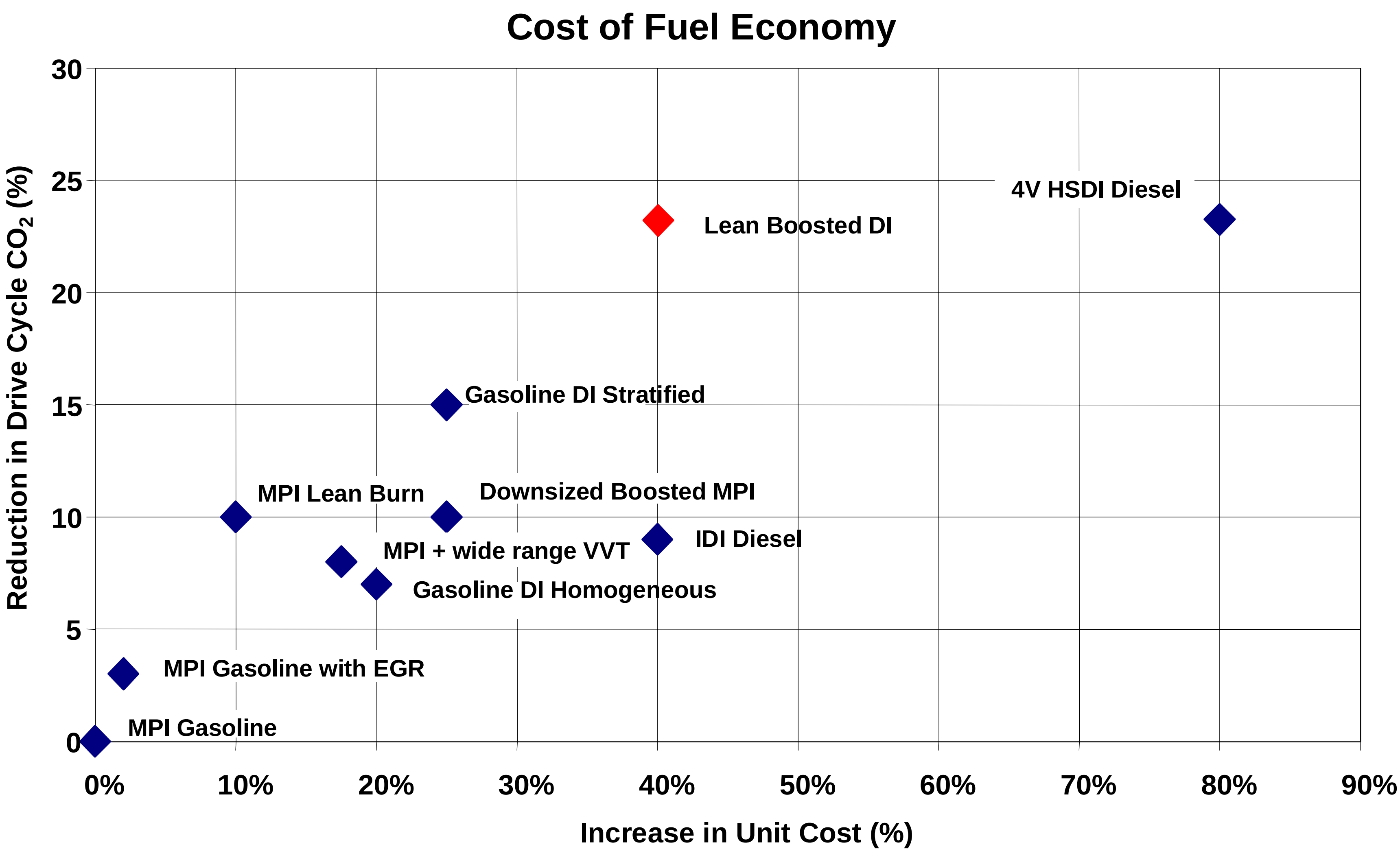
Cummins:	**Exhaust Gas Recirculation (EGR) for No_x reduction and efficiency improvement**
	Variable Geometry Turbochargers
	Higher injection pressures
	Aftertreatment: Oxidation catalysts (PM)
Navistar:	**Vertical injectors and four valve head**
	Cooled EGR
	Port deactiviation
	HEUI (hydraulically activated engine unit controlled injection)
	AVNT (advanced variable nozzle turbocharger)
	Aftertreatment: Lean NO_x catalysts, NO_x absorbers, PM traps
Detroit Diesel:	**EGR**
	Electronic Controls
	Aftertreatment: Oxidation catalysts (PM), SCR (NO_x)
Other Manufacturers:	**Shrouded Port Turbochargers, Variable Nozzle Turbochargers, Variable Valve Timing, Electronic Valve Activation, Common Rail Fuel Systems, Cooled EGR Particulate Traps, Lean NO_x Traps**

Source: Presentations given at the 3rd Biennial World Truck Conference, Monterey, California, March 4-6, 2001.

Aftertreatment System Engineering
Large SUV: SCR + DPF For LEV II



Powertrain Options



Emissions and Efficiency Targets: Conclusions

EMISSIONS:

- Emissions technology driven primarily by Federal, State, and Local legislation
- Emissions technology includes both combustion modifications and aftertreatment systems
- Current technology will allow attainment of ARB and EPA Tier 2 and Tier 3 limits

Popular technologies will be:

- Advanced Fuel Injection and combustion chamber design
- Advanced aftertreatment - PM traps, SCR, NO_x Absorber, Oxidation Catalysts
- Integrated system control strategies
- EGR (including cooled EGR)

Emissions and Efficiency Targets: Conclusions

EFFICIENCY:

- Improved diesel engines have thermal efficiencies approaching those of fuel cells.
- Fuel efficiency improvements of over 20% are expected during the next 10 years.

Popular technologies will be:

- Advanced Fuel Injection and combustion chamber design (port deactivation, swirl control, lean burn, bowl design)
- Improved Electronic Controls
- Variable valve timing, electronic valve actuation
- Integrated system control strategies
- Turbocharger improvements (variable geometry, unit injection)

Conclusions

- **Significant changes in the internal combustion engine over the next decade will impact strongly on fuel and lubricant requirements**
  - Low Sulfur Fuel
  - Lubricant effects on emissions

- **Beyond 2010, the challenge will continue**
  - Alternative fuels
  - New combustion technologies